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Formation of a Massive Black Hole at the Center of the Superbubble in M82

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ABSTRACT

We performed ^{12}CO$(1-0)$, ^{13}CO$(1-0)$, and HCN$(1-0)$ interferometric observations of the central region (about 450 pc in radius) of M82 with the Nobeyama Millimeter Array, and have successfully imaged a molecular superbubble and spurs. The center of the superbubble is clearly shifted from the nucleus by 140 pc. This position is close to that of the massive black hole (BH) of $\gtrsim 460$ $M_\odot$ and the 2.2μm secondary peak (a luminous supergiant dominated cluster), which strongly suggests that these objects may be related to the formation of the superbubble. Consideration of star formation in the cluster based on the infrared data indicates that (1) energy release from supernovae can account for the kinetic energy of the superbubble, (2) the total mass of stellar-mass BHs available for building-up the massive BH may be much higher than 460 $M_\odot$, and (3) it is possible to form the middle-mass BH of $10^2 - 10^3$ $M_\odot$ within the timescale of the superbubble. We suggest that the massive BH was produced and is growing in the intense starburst region.

Subject headings: black hole physics, galaxies: individual (M82, NGC 3034), galaxies: ISM, galaxies: starburst, ISM: bubbles

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1. INTRODUCTION

A starburst is a star formation event with a high star formation efficiency. This usually occurs in the galactic nuclear/central regions. Starbursts and successive supernova explosions cause drastic changes in kinematic and physical conditions of interstellar medium, and produce (expanding) superbubbles, chimneys, and/or large-scale outflows. There is observational evidence for these structures in hot and/or atomic gas in many galaxies (e.g. Fabbiano 1989; Tenorio-Tagle & Bodenheimer 1988), but there is much less clear evidence in molecular gas. Starburst phenomena in the nuclear regions are also thought to be closely related to active galactic nuclei (AGNs) powered by massive black holes (MBHs; more massive than a stellar-mass BH), such as fueling AGNs and/or causing the growth of MBHs. One question, "can starbursts produce the seeds of MBHs or middle-mass BHs?," is still largely unresolved.

Nearby (3.25 Mpc; Sandage & Tammann 1975) irregular galaxy M82 (NGC 3034) has kiloparsec scale bipolar outflows which can be seen by optical emission lines (e.g. Shopbell & Bland-Hawthorn 1998) and X-ray (e.g. Bregman et al. 1995) (Fig. 1a). This outflow is believed to be made by frequent supernova explosions at the central region in consequence of starburst. Recent X-ray studies have found evidences of an MBH with a mass of $\gtrsim 460 M_\odot$ in the starburst region (Matsumoto & Tsuru 1999; Ptak & Griffiths 1999). In this region, however, strong dust absorption prevents detailed optical/near-infrared observations, so we performed millimeter-wave observations which would not be affected by the dust.

2. OBSERVATIONS

Aperture synthesis observations of the central region of M82 were carried out in the ^{12}CO, ^{13}CO, and HCN $J = 1 \rightarrow 0$ lines (rest frequency = 115.271 GHz, 110.201 GHz, and 88.632 GHz, respectively) with the Nobeyama Millimeter Array (NMA) during 1997 November - 1999 March. All the images were obtained using three configurations of six 10m antennas which are equipped with tunerless SIS receivers (Sunada et al. 1994), and the system noise temperatures in the single side band were about 950 K, 850 K, and 450 K at 115 GHz, 110 GHz, and 89 GHz, respectively. As a back-end, we used an XF-type spectro-correlator Ultra Wide Band Correlator (UWBC; Okumura et al. 2000), with a total bandwidth of 512 MHz over 256 channels for the ^{12}CO observations (corresponding to 1300 km s^{-1} bandwidth with 5.2 km s^{-1} velocity resolution), and with a total bandwidth of 1024 MHz over 128 channels for the ^{13}CO and HCN observations (corresponding to 2800 km s^{-1} and 3500 km s^{-1} bandwidths with 22 km s^{-1} and 27 km s^{-1} velocity resolutions, respectively). The band-pass calibration was done with 3C273, and 0923+392 was observed every 10 minutes as a phase and amplitude calibrator. The flux scale of 0923+392 was determined by comparisons with Mars and Uranus, and has an uncertainty of $\sim 20\%$.

3. EXPANDING MOLECULAR SUPERBUBBLE

The overall distribution in the ^{12}CO total integrated intensity map shows diffuse spurs north and south (minor axis direction) of the galaxy, in addition to the previously identified (Shen & Lo 1995) three prominent peaks (the so-called North-East [NE] and South-West [SW] lobes and a central peak). These spurs trace the dark filaments which can be seen in optical B-band images (Alton et al. 1999) (Fig. 1b). Similar structures have been detected further out in the filaments (Nakai et al. 1987; Kuno & Matsuo 1997; Alton et al. 1999) which are connected to the large-scale Hα and X-ray outflow (Shopbell & Bland-Hawthorn 1998; Bregman et al. 1995) (Fig. 1a), but ours is the first detection close to the disk.

A position-velocity (PV) diagram of ^{12}CO data cut along the major axis of the galaxy (Fig. 2b) shows an arc-like deviation from rigid rotation between the central peak and the SW lobe. Such deviations are common features of expanding H I superbubbles (Deul & den Hartog 1990). In addition, recent literature also suggests that this deviation implies the existence of a molecular superbubble (Neininger et al. 1998; Weiβ et al. 1999; Wills et al. 1999). However, any shell structures have not been detected in spatial image so far, and Weiβ et al. (1999) concluded that the superbubble had already broken toward the minor axis direction of this galaxy. We made a channel map, binning over the velocity range $V_{\rm LSR}$ = 118 to 212 km s^{-1}, which corresponds to the range deviates from the rigid rotation (Fig. 1c). The map clearly shows a shell-like structure, with a diameter of $\sim$ 210 pc $\times$ 140 pc ($\sim 14'' \times 9''$) elongated toward north-south direction, between the two peaks. This structure is also visible in other molecular lines such as ^{13}CO (Fig. 1d) and HCN (Fig. 1e). These images indicate that the superbubble is still not broken out of the galactic disk. Around the superbubble, however, there are some spurs connecting with the shell structure, so that it may be possible that some parts of the superbubble were already broken.

If we assume that the shell structure is the result of edge-brightening (Wills et al. 1999), the southern part of the shell should be moving perpendicular to the line-of-sight with nearly the rigid rotation velocity, which corresponds to the systemic velocity of the molecular superbubble. Indeed, the velocity field of the southern shell is very close to rigid rotation (Fig. 2c). In addition, the PV diagram shows that almost all of the molecular gas except that of the superbubble is on the rigid rotation (Fig. 2b). These reasons lead us to conclude that the expansion velocity of the superbubble is the largest velocity deviation from the rigid rotation seen in the PV diagram; the resultant expansion velocity is $\sim$ 100 km s^{-1}. However, we cannot reject the possibility of an expansion velocity of $\sim$ 50 km s^{-1}, which is the mean velocity deviation in the PV diagram (Weiβ et al. 1999), so we use the velocity range of 50 – 100 km s^{-1} for the following calculations. Using the velocity and the size of the superbubble derived above, the elapsed time from the explosion can be estimated as $\sim (1-2) \times 10^6$ years. Weiβ et al. (1999) also derived similar timescale of 1×10^6 years.

Next, we will estimate the energetics of the superbubble. Using the intensity ratios between the ^{12}CO line and the ^{13}CO and HCN lines, we calculated the CO-to-H$_2$ conversion factor based on the Large-Velocity-Gradient (LVG) approximation (Sakamoto 1999). The resultant conversion factor is $(1.4 \pm 0.6) \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, which is consistent with the previous observations of $\sim (1.0-1.2) \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ (Wild et al. 1992; Smith et al. 1991). Hence, we adopted our estimated value, and the calculated molecular superbubble mass would be $\sim 1.8 \times 10^8$ M$_\odot$. From this molecular gas mass and the expansion velocity, we derive the kinetic energy of the superbubble to be $\sim (0.5-2) \times 10^{55}$ erg, equivalent to the total energy of $\sim 10^3 - 10^4$ supernovae, and an order of magnitude or more larger than that observed in H I superbubbles in other galaxies ($< 10^{54}$ erg; Tenorio-Tagle & Bodenheimer 1988). The energy estimated by Weiβ et al. (1999) was $\sim 2 \times 10^{54}$ erg, similar to ours, although their estimation have a large ambiguity in the volume of the material swept up by the explosion.

4. MASSIVE BLACK HOLE INSIDE THE SUPERBUBBLE

At the center of the superbubble, there is a hard X-ray variable point source and a 2.2 μm secondary peak (Fig. 1c); hard X-ray observations with ASCA indicate that there is a strong point source located in the central region of M82. This source shows time variability in its intensity, which indicates the existence of a MBH with its mass of $\sim 460 - 2 \times 10^8$ M$_\odot$ (Matsumoto & Tsuru 1999; Ptak & Griffiths 1999). Comparing the ROSAT HRI image (Bregman et al. 1995; Stevens et al. 1999) with the false ROSAT image made from ASCA data (the image using similar energy-band with that of ROSAT), it was found that the position of the hard X-ray variable source is consistent with that of the X-ray peak detected with the ROSAT (Matsumoto & Tsuru 1999). Detailed comparison between the location of this point source and our newly obtained ^{12}CO map, reveals that the X-ray point source is located at the center of the superbubble. Recent high resolution X-ray observations with Chandra show that there is a variable source inside the superbubble with its peak luminosity of $\sim 9 \times 10^{40}$ erg s^{-1}, assuming this source has a same spectrum as the ASCA variable source (Matsumoto et al. 2000). This result also supports the conclusion that there is a MBH inside the superbubble. On the other hand, the emission from the 2.2 μm secondary peak (Dietz et al. 1986; Lester et al. 1990) seems to be dominated by luminous supergiants (Joy et al. 1987), which suggest that it is a late phase dense starburst cluster.

Since these objects are located close to the center of the superbubble, it is natural to think that these objects are related to the superbubble's formation. We therefore discuss the possibility that the starburst at the 2.2 μm secondary peak produces the superbubble and the MBH. We first calculated the stellar population of this 2.2 μm secondary peak cluster assuming an initial mass function (IMF), and estimated the starburst evolution as follows: The luminosity of the 2.2 μm secondary peak with an extent (full width at half maximum) of $4''$ (McLeod et al. 1993) is equivalent to ~ 1500 M2 supergiants. We assume that stars with initial mass larger than 30 M$_\odot$ (short-lived stars with lifetimes $< 2 \times 10^6$ yr; Lang 1998) have already exploded as supernovae, and that the remaining stars with initial masses of $25 - 30$ M$_\odot$ are now M2 supergiants. Using an extended Millar-Scalo IMF (Kennicutt 1983) of $dN/dm \propto m^{-2.5}$ with lower and upper mass limits of 1 and 100, and assuming that there are 1500 stars whose masses are $25 - 30$ $M_\odot$, the total stellar numbers and the total mass formed at the 2.2 μm secondary peak cluster would be about 8×10^5 stars and 2×10^6 $M_\odot$, respectively. The number of ≥ 30 $M_\odot$ stars which would have already exploded in this cluster is $\sim 4 \times 10^3$, consistent with the estimated number of supernovae needed to create the superbubble ($10^3 - 10^4$). The observational evidence and IMF calculations suggest that the expanding molecular superbubble may be a result of localized starbursts which occurred around the position of the 2.2 μm secondary peak.

We next discuss the possibility of making a MBH at the starburst in M82. If we assume that stars with initial mass of > 25 $M_\odot$ would create stellar-mass BHs of almost the same mass (Brown & Bethe 1994), there would be $\sim 4 \times 10^3$ BHs with a total mass of $\sim 2 \times 10^5$ $M_\odot$ in the 2.2 μm secondary peak cluster. Assuming an isothermal sphere stellar density distribution (Lee 1995), about 4×10^3 $M_\odot$ BHs would sink into the cluster center by dynamical friction within 2×10^6 yr. This mass is well within the range of that of the MBH estimated from the hard X-ray observations. There is also a possibility of star-star merger. If we assume a merging probability of 0.1% in the cluster, which is a similar probability to the simulations of stellar mergers in star clusters (Portegies Zwart et al. 1999), it is possible to make one ~ 700 $M_\odot$ star, or several stars of a few hundred $M_\odot$, in the cluster. Explosions of such very high mass stars can produce $\gtrsim 10^{52}$ erg or even 10^{54} erg energy hypernovae (e.g. Paczyński 1998), which can be seen as γ-ray bursts, and may possibly have created the superbubble and MBH. If we set the lower limit of the BH mass, $M_{\rm BH}$, in this cluster using the hard X-ray observations, and the upper limit using the total mass of the stars which seem to be already exploded (≥ 30 $M_\odot$), the range of the BH mass would be $460 - 2 \times 10^5$ $M_\odot$. This mass range suggests that this MBH might be a middle-mass BH. Since the cluster mass, $M_{\rm cluster}$, is calculated as 2×10^6 $M_\odot$ using the IMF, the ratio of $M_{\rm BH}$ to $M_{\rm cluster}$ would be $-3.6 \lesssim \log(M_{\rm BH}/M_{\rm cluster}) \lesssim -1.0$. As shown in Figure 3, this range is on the $M_{\rm bulge}$-$M_{\rm BH}$ relation for galaxies with supermassive BHs (Magorrian et al. 1998).

Since there are many other clusters in the central region of M82, another question, “why other clusters do not have MBHs?,” would arise. One possibility is lack of stellar density. If their densities are small, the effect of dynamical friction or star-star merging rate may decrease and it may not be possible to make massive objects. The low density clusters would also be affected by tidal force (e.g. Taniguchi et al. 2000) and tend to be smaller clusters which are not large enough to make massive objects. There is another possibility that the MBH was not created at the cluster but supplied from satellite galaxy by minor merger (e.g. Taniguchi et al. 2000). In this case, there are two possibilities of the agreement between the position of the MBH and that of the superbubble; one is just accidentally overlapping each other, and another is that the superbubble is created by the MBH. A BH merging with a compact object (neutron star, white dwarf, etc.) can cause a large energy release ($\sim 10^{54}$ erg; Mészáros et al. 1999). If the MBH meets with a cluster on the way sinking toward the galactic center, there are possibilities to merge with some compact objects, and as a result, energetic explosions would occur and the superbubble would be made. These discussions still have large ambiguities because of lack of detailed information, so that further observations with many wavelengths/frequencies would be needed.

In future, this middle-mass BH may increase its mass. Since massive stars still exist ($\sim 10^5$ $M_\odot$) at the 2.2 μm secondary peak cluster, it is possible to feed stars and/or stellar-mass BHs to the middle-mass BH. Also, the middle-mass BH is still not at the dynamical center of M82, and it may sink down to the center with dynamical friction, where mass is strongly concentrated. Therefore there are many ways for the middle-mass BH in M82 to increase in mass and therefore grow up to the supermassive BH. Our results may give a new explanation to the reason why some of the quasars are embedded in interacting (and therefore active star forming) galaxies, and strong γ-ray bursts and middle-mass BHs are located either at or offset from galactic nuclei.

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Fig. 1.— Various scale images of M82. In molecular gas images, value for the colorscale is indicated on the top of each figure, and the plus mark indicates the position of the galactic nucleus determined from the peak of the strongest 2.2μm source (Lester et al. 1990). (a) The X-ray image (contours; Bregman et al. 1995) overlaid on the Hα image (grayscale; Shopbell & Bland-Hawthorn 1998). (b) ^{12}CO integrated intensity map (contours) overlaid on optical B-band image (grayscale; Alton et al. 1999). Bright regions on the grayscale are indicated in black and dark regions are in white. The contour levels of the ^{12}CO map are $5, 10, 15, 20, 25, 30, 40, 50, \cdots, 90\sigma$, where 1 σ = 1.64 Jy beam^{-1} km s^{-1} [= 23 K km s^{-1}]. The synthesized beam ($2''.8 \times 2''.3$ or 42 pc $\times$ 35 pc) is shown at the bottom-left corner. (c) The ^{12}CO molecular superbubble image, binning over the velocity range of $118 - 212$ km s^{-1}. The contour levels of the ^{12}CO map are $-10, 10, 20, 30, \cdots, 110\sigma$, where 1 σ = 8.9 mJy beam^{-1} [= 127 mK]. The synthesized beam size is the same as (b). The diamond mark and the filled circle indicate the central positions of the 2.2μm secondary peak (Dietz et al. 1986), and the X-ray point source observed with ROSAT (Stevens et al. 1999) which corresponds with the ASCA hard X-ray variable source position (Matsumoto & Tsuru 1999). We also indicate the recently observed Chandra X-ray variable source (Matsumoto et al. 2000) with a circle, which radius corresponds to its position uncertainty. (d) The HCN molecular superbubble image, binning over the velocity range of $134 - 215$ km s^{-1}. The contour levels of the HCN map are $-6, -3, 3, 6, 9, 12, 15\sigma$, where 1 σ = 3.7 mJy beam^{-1} [= 39 mK]. The synthesized beam ($4''.1 \times 3''.6$ or 62 pc $\times$ 54 pc) is shown at the bottom-left corner. (e) The ^{13}CO molecular superbubble image, binning over the velocity range of $127 - 214$ km s^{-1}. The contour levels of the ^{13}CO map are $-3, 3, 6, 9, 12, 15, 18\sigma$, where 1 σ = 5.4 mJy beam^{-1} [= 41 mK]. The synthesized beam ($3''.9 \times 3''.4$ or 59 pc $\times$ 51 pc) is shown at the bottom-left corner.

Fig. 2.— Position-velocity (PV) diagrams of M82. Values for the colorscale are indicated on the top of each figure. (a) ^{12}CO integrated intensity map. Solid lines indicate the sliced regions for PV diagrams displayed below. The plus mark is the same as Fig. 1b. (b) PV diagram at slice A. The solid line indicates rigid rotation velocity. The region of the superbubble (around α(B1950)=$9^{\rm h}51^{\rm m}43^{\rm s}.6$) clearly deviates from the rigid rotation velocity. (c) PV diagram at slice B. The solid line indicates rigid rotation velocity. Almost all of the gas at this slice is on the rigid rotation velocity.

Fig. 3.— Correlation diagram between the mass of black holes ($M_{\rm BH}$) and those of the host bulges or clusters ($M_{\rm bulge}$) in galaxies. The bar mark indicates the estimated mass range of the middle-mass BH in M82, assuming its host corresponds to the 2.2 μm secondary peak cluster. The upper limit of the middle-mass BH mass and the 2.2 μm secondary peak cluster mass have been estimated from IMF calculations, and the lower limit of the BH mass has been estimated from the hard X-ray observations. Cross marks indicate the data taken from Magorrian et al. (1998), and a solid line is a linear fitting of their data. We did not include their upper limit data in this diagram. This figure clearly shows that the data of M82 is on the trend of the mass of the supermassive black holes and those of the host bulges.